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Model based decision support system of operating settings for MMAT nozzles

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Abstract: Droplet size, which is affected by nozzle type, nozzle setups and operation, and spray solution, is one of the most critical factors influencing spray performance, environment pollution, food safety, and must be considered as part of any application scenario. Characterizing spray nozzles can be a timely and expensive proposition if the entire operational space (all combinations of spray pressure and orifice size, what influence flow rate) is to be evaluated. This research proposes a structured, experimental design that allows for the development of computational models for droplet size based on any combination of a nozzle's potential operational settings. The developed droplet size determination model can be used as Decision Support System (DSS) for precise selection of sprayer working parameters to adapt to local field scenarios. Five nozzle types (designs) were evaluated across their complete range of orifice size (flow rate*) and spray pressures using a response surface experimental design. Several of the models showed high level fits of the modeled to the measured data while several did not as a result of the lack of significant effect from either orifice size (flow rate*) or spray pressure. The computational models were integrated into a spreadsheet based user interface for ease of use. The proposed experimental design provides for efficient nozzle evaluations and development of computational models that allow for the determination of droplet size spectrum and spraying classification for any combination of a given nozzle's operating settings. The proposed DSS will allow for the ready assessment and modification of a sprayers performance based on the operational settings, to ensure the application is made following recommendations in plant protection products (PPP) labels.

Key words: droplet size classification, droplet size determination, DSS, spraying classification, modeling, sprayer adjustment, sprayer operating settings

Introduction

Ensuring maximum biological efficacy of an agrochemical spray application, while mitigating off-target movement, requires consideration of the setup of the sprayer system. It needs particularly with respect to nozzle selection and operation. Both of which significantly affect the resulting droplet size, which in turn significantly influences spray deposition, biological efficacy, PPP losses (aerial drift, volatilization, ground sediment) (Hewitt 1997a, b; Matthews 2000; Dorr *et al*. 2013), and residues (Czaczyk and Gnusowski 2007). Through the use of different nozzle types and sprayer operational settings, the generated droplet size spectra can easily be influenced across a wide range of available potential of droplet sizes. These parameters are critically important in providing advice to supporting plant protection (Doble *et al.* 1985; Gajtkowski 1985; Matthews 2000; Giles *et al.* 2005; Czaczyk 2013). Knowing the actual atomization characteristics and, particularly, droplet size classification, can be difficult as actual droplet size information is not typically provided by a nozzle manufacturer across large combination of flow rate and operational pressures within a given nozzle type.

The description flow rate* for nozzle designation is more adequate to use, because for air induction nozzles the flow rate is determined at the inlet (diameter). The size of outlet (cross area and geometry) of flat fan nozzles influence the form of spray shape – the spray angle and atomization characteristics (Dorr *et al*. 2013). The description of orifice size e.g. 02 (i.e. two US liquid gallons per minute at 276 psi pressure) comes from the *visiflo* system proposed in 1983 by Spraying Systems Co.®. For the agricultural nozzles exist since 2005 an international standard in metric units ISO 10625 (2005). For the description 02, at 300 kPa pressure, the flow rate is 0.8 $l \cdot min^{-1}$ (±5% tolerance).

Developing databases of droplet size data and classification for a given nozzle type can be time consuming and expensive given the large number of potential combinations of flow rate* and pressure for any given nozzle (Czaczyk 2012a, b; Douzals 2012; Dorr *et al*. 2013; Fritz *et al*. 2014a, b). As an example a typical flat fan type nozzle may have as many as 10 (or in some cases more) flow rate* available, and may have a recommended operational pressure range covering 100 to 800 kPa. Were every flow rate* to be tested at each 100 kPa of pressure, 80 treatment

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points would have to be evaluated to provide droplet size data that covered this nozzles full operating range.

Kirk (2007) applied a response surface method (RSM) experimental design, which uses a coded set of treatment combinations from the potential factors influencing atomization phenomenon and droplet size. This original application of the RSM design focused on aerial application spray nozzles whose droplet size was influenced by four primary factors, for a given nozzle type. These included flow rate*, spray pressure, air speed and nozzle orientation. This method used a set of 27 experimental data points that allowed for the development of a second-order regression equation that calculated droplet size based on user-defined specifications of the four main factors (Kirk 2007). This method was further applied to a limited set of ground application spray nozzles used in the United States of America and was shown to provide high levels of fit from the model when compared to independently evaluated tested points (Fritz *et al*. 2016).

The evaluation of droplet size from agricultural sprays is potentially impacted by the measurement method (Hammond 1981; Tishkoff 1984; Hewitt 1997a) and instrumentation (Dodge 1987) used. While a detailed discussion of these factors is beyond the scope of this work Fritz *et al*. (2014b), has shown that careful attention to measurement setups and operational settings can lead to droplet size results with inter- and intra-laboratory repeatability and precision. The methods developed in that work are adopted for this study and discussed in greater detail in the methods.

The objective of this work was to evaluate a set of ground nozzles used for agrochemical applications in Poland, using a definitive screening response surface model experimental design to develop predictive droplet size models for each. Further, to evaluate the complete operational space to better understand the spray characteristics of each nozzle tested, and provide to plant protection products (PPP) application advisors as a Decision Support System (DSS) at no cost.

Materials and Methods

Ground application nozzles were evaluated for droplet size following a definitive screening experimental design. The measured data were fit to a mathematical prediction expression in the form of a response surface. The completed models were integrated into an Excel spreadsheet user interface that provides both droplet size and classification data to the user. Droplet measurement and data analysis methods as well as the nozzles tested and experimental design used are discussed in the following sections.

Definitive screening designs for response surface models

Five different types of flat fan nozzles (multiple designs) were selected for testing (Table 1). These nozzles produced according standards: ISO 10625 (2005), ISO 8169 (1984) (Czaczyk and Szulc 2012), represent those typically used in Poland for agricultural ground spray applications. Study conducted on MMAT nozzles, for an optimized use them for crop protection, according requirements of PPP labels. Each nozzle was evaluated over a range of flow rate* and spray pressures, as specified in Table 1.

All experimental designs were developed and data processing completed using JMP® (Version 11.1.1, 2013 SAS Institute). For all tested nozzles, flow rate* was set in the model as a discrete factor with each flow rate* available set as a level (flow rate* available given in Table 1). Spray pressure was set as a continuous variable with maximum and minimum values as given in Table 1. The final developed models are only applicable across the range of parameters tested and cannot be extended beyond. Treatment lists for each nozzle are given in Tables 2–6. Note that there are some treatments that are identical in each treatment list, these are specified by the experimental design and are typically in the center of the operational space and provide for an increased fit of the model. These runs were separated by a different treatment and not analyzed as a continuous set of replications.

Droplet size measurements

All droplet-sizing measurements were performed at the United States Department of Agriculture (USDA), Agricultural Research Service (ARS) Aerial Application Technology Research Unit's laboratory located in College Station, Texas. A low speed (0.4 – 8.0 $m \cdot s^{-1}$ air speed range) airflow tunnel (1.2 by 1.2 m, by 9.8 m long) was used to provide concurrent airflow (Rh ~70%, t ~20°C) to the nozzle. A concurrent airflow of 6.7 $m \cdot s^{-1}$ was used (Hewitt 1997a, b – who first determined the wind tunnel speed necessary to mitigate spatial sampling bias) in all nozzle evaluations to minimize spatial sampling errors with the laser diffraction system (Fritz *et al*. 2012, 2014a). The nozzle positioned upstream of the tunnel exit and 30.5 cm upstream of the line of measurement. All droplet sizing was conducted using a spray solution of water (t ~20°C) with a $0.25\%_{v/v}$ of a 90% non-ionic surfactant (NIS) R-11® (Wilbur-Ellis, USA) (Miller and Tuck 2005), which resulted in a solution with a dynamic surface tension of 0.050 $N \cdot m^{-1}$ (at 20 ms) and a shear viscosity of 0.44 cP (required in ANSI/ASAE S572.1 standard). This solution was fed to the nozzle from a 19 l stainless steel pressure tank that was pressurized using an air compressor (Campbell Hausfeld, USA). A pressure regulator was used to adjust air pressure into the tank to vary spray pressure at the nozzle. The spray pressure at the nozzle was controlled at each run with and electronic pressure gauge (PX409-100GUSB, Omega Engineering, Stanford CT).

All droplet size data was measured using a Sympatec HELOS Vario/KR® laser diffraction system (Sympatec GmbH, Clausthal-Zellerfeld, Germany) that was operated using the manufacturer denoted R7 lens which has a dynamic size range of ∅18–3,500 µm across 31 bins. Both the concurrent air stream velocity and the measurement distance were determined from previous work (Fritz *et al*. 2014a) to minimize spatial sampling error, and are now standard methods at several droplet size laboratories (Fritz *et al*. 2014b). Evaluation of each treatment consisted of a series of replicated measurements, each of which wasone full vertical traverse of the spray plume at a rate of 6.4 cm · s^{-1}. A sufficient number of replications were made to ensure that the standard deviations of $D_{v0.1}$, $D_{v0.5}$ (VMD), and $D_{v0.9}$ (the 10, 50 and 90% volume diameters, VMD – volume median diameter) were within ±5% of the means (minimum of three replications). Additionally, the percent volume of the spray ($V_{<100}$) contained in droplets of diameter below ∅100 µm ($\%_{vol}$) was also recorded (ASABE 2012; Czaczyk 2013, 2014). Recorded droplet size data is included in Tables 2–6 alongside the nozzle/pressure combinations evaluated.

Droplet size classification

The reference nozzles, as specified by the ANSI/ASAE S572.1 spray classification standard (ASABE 2009), were evaluated for droplet size as part of this work. The reference used nozzles were a set obtained from Spraying Systems Co.® (Wheaton, IL) that were flow rated to meet the levels specified in the standard. Droplet size measurements were taken for each nozzle at the reference pressures specified (ASABE 2009) [450, 300, 200, 250, 200 and 150 kPa for the 11001, 11003, 11006, 8008, 6510, and 6515 nozzles (ISO 10625), respectively].

Table 1. Nozzles evaluated using the response surface experimental design method and the flow rate* and pressure ranges tested

Nozzle design (ISO 8169)	Manufacturer (design[1])	Flow rate* (ISO 10625)	Pressure range [kPa]
EZ	MMAT (AI)	015 to 08	100–600
EZK	MMAT (AI)	02 to 06	100–600
EZKT	MMAT (AIT)	02 to 08	100–600
AZ	MMAT (RD)	015 to 05	100–500
RS	MMAT (FF)	01 to 20	100–500

[1]design abbreviation: AI – air induction; AIT – AI-twin jet; RD – pre orifice; FF– standard flat fan

Table 2. Definitive screening model treatment list for the EZ nozzle

Run number	Flow rate*	Pressure [kPa]	$D_{v0.1}$ [µm]	$D_{v0.5}$ [µm]	$D_{v0.9}$ [µm]	$V_{<100}$ [$\%_{vol}$]
1	015	390	170	384	707	2.7
2	02	600	121	263	484	6.3
3	025	250	158	365	695	3.1
4	03	430	168	376	657	2.6
5	03	430	169	381	681	2.6
6	05	600	171	385	648	2.4
7	06	250	197	439	715	1.6
8	06	430	169	384	642	2.7
9	06	430	183	409	673	2.2
10	08	250	219	491	814	1.2
11	08	600	166	382	653	2.8

Table 3. Definitive screening model treatment list for the EZK nozzle

Run number	Flow rate*	Pressure [kPa]	$D_{v0.1}$ [µm]	$D_{v0.5}$ [µm]	$D_{v0.9}$ [µm]	$V_{<100}$ [$\%_{vol}$]
1	015	200	254	526	786	0.6
2	015	600	161	350	577	2.5
3	025	400	146	322	551	3.7
4	025	400	145	319	556	3.7
5	04	200	213	460	735	1.1
6	04	600	148	323	544	3.3
7	06	400	177	391	673	2.1
8	06	400	173	383	652	2.3
9	06	400	172	378	642	2.3
10	08	200	210	456	747	1.3
11	08	600	139	310	556	4.1

Table 4. Definitive screening model treatment list for the EZKT nozzle

Run number	Flow rate*	Pressure [kPa]	$D_{v0.1}$ [µm]	$D_{v0.5}$ [µm]	$D_{v0.9}$ [µm]	$V_{<100}$ [$\%_{vol}$]
1	02	200	139	310	556	4.1
2	02	600	260	501	735	0.5
3	03	400	126	275	481	5.2
4	03	400	149	328	568	3.4
5	04	200	146	325	568	3.6
6	05	600	176	391	641	1.9
7	06	400	105	251	463	8.8
8	06	400	154	355	602	3.2
9	06	400	156	359	608	3.1
10	08	200	153	354	600	3.3
11	08	600	217	482	814	1.2

Table 5. Definitive screening model treatment list for the AZ nozzle

Run number	Flow rate*	Pressure [kPa]	$D_{v0.1}$ [µm]	$D_{v0.5}$ [µm]	$D_{v0.9}$ [µm]	$V_{<100}$ [$\%_{vol}$]
1	01	150	82	188	348	16.0
2	01	500	61	137	251	30.2
3	02	325	69	159	300	23.4
4	02	325	69	159	298	23.4
5	03	150	114	273	477	7.1
6	04	500	87	199	357	13.7
7	05	325	101	241	440	9.9
8	05	325	101	239	434	9.7
9	05	325	101	244	442	9.7
10	06	150	143	337	600	3.7
11	06	500	100	238	444	9.9

Table 6. Definitive screening model treatment list for the RS nozzle

Run number	Flow rate*	Pressure [kPa]	$D_{v0.1}$ [µm]	$D_{v0.5}$ [µm]	$D_{v0.9}$ [µm]	$V_{<100}$ [$\%_{vol}$]
1	01	310	56	120	222	37.0
2	02	500	59	130	237	32.4
3	03	150	102	224	408	9.4
4	06	325	93	219	419	11.8
5	06	325	94	223	434	11.5
6	10	500	107	266	538	8.6
7	15	150	168	393	768	2.2
8	15	325	128	330	676	5.6
9	15	325	126	329	688	5.8
10	20	150	190	455	908	1.5
11	20	500	139	361	716	4.7

Data processing

All data collected for this work were processed using the JMP® (Version 11.1.1, 2013 SAS Institute). These $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, and $V_{<100}$ were coded as the response variables for each nozzle treatment. A standard least squares analysis was used to fit a model to a second-order response relationship with factors X_1 [flow rate* (ISO 2005)] and X_2 (spray pressure) (Eq. 1). The two constants C_{subi} and C_{divi} are subtraction and division terms, respectively, used to adjust each X_i input term to a value between –1 and 1. These values are unique to each nozzle and are dependent on the maximum and minimum flow rate* and spray pressures.

$$Y = A + B\left(\frac{X_1 - C_{sub1}}{C_{div1}}\right) + C\left(\frac{X_1 - C_{sub1}}{C_{div1}}\right)^2 + D\left(\frac{X_2 - C_{sub2}}{C_{div2}}\right) + E\left(\frac{X_1 - C_{sub1}}{C_{div1}}\right)\left(\frac{X_2 - C_{sub2}}{C_{div2}}\right) + F\left(\frac{X_2 - C_{sub2}}{C_{div2}}\right) \quad \text{(Eq. 1)}$$

where:
Y = atomization parameter to be predicted based on input combination of X_1 through X_2 (i.e. $D_{v0.1}$, $D_{v0.5}$, etc.);
X_1 = flow rate* (unitless, specific orifice number for each nozzle according ISO 10625 (2005);
X_2 = spray pressure (bar), (100 kPa = 1 bar);
C_{subi} = constant subtraction term;
C_{divi} = constant dividend term;
A to F = constant coefficients for each term of the prediction expression (unitless and unique for each nozzle).

Once the final models were developed, the entire operational space, across all combinations of spray pressure and flow rate* was evaluated for droplet size classification (DSC). To determine DSC for each nozzle operational point, the $D_{v0.1}$, $D_{v0.5}$ values were compared to those from the ASABE reference nozzles with DSC being determined following the methods outline by the standard. To evaluate all operational combinations for each nozzle, a custom FORTRAN (Simply Fortran Ver. 2.15, Approximatrix LLC) code was used. The results were then evaluated to determine overall DSC percentage across each operational space of each nozzle.

Results

Computational model parameters

The parameters *A* through *F* for each nozzle tested, as well as the C_{subi} and C_{divi} for each of the nozzles tested are given in the Appendix in Tables A1 through A6. Using these values and Equation 1, droplet size parameters can be calculated for combinations of flow rate* (X_1) and spray pressure (X_2) that fall within the ranges specified for each nozzle (Table 1). The figure 1 shows an example of calculated atomization characteristics for EZ 11002 nozzle.

EZ nozzle

The R^2 values for the response surface models (RSM) were 0.80, 0.80, 0.75 and 0.74 for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$ curve fits, respectively. Previous models developed for typical flat fan, air induction flat fan, and twin jet flat fan and air induction flat fan nozzles have typically had R^2 values of 0.92 or higher (Fritz *et al*. 2016). The flow rate* and pressure were significant factors for $D_{v0.1}$ (p values of 0.0246 and 0.0420, respectively). However, flow rate* by flow rate*, pressure by pressure, and flow rate* by pressure effect were not significant. Similar results were seen with $D_{v0.5}$ with flow rate* and pressure being significant (p values of 0.0226 and 0.0354, respectively) and the other parameters not significant. As observed at the $D_{v0.9}$ only pressure was a significant factor (p = 0.0238) and for $V_{<100}$ none of the parameters were significant. The actual droplet size data shows that these results are not surprising as $D_{v0.1}$ data ranges from ∅120 to 220 μm across all flow rate* and pressure combinations, while $D_{v0.5}$ data ranges from ∅263 to 439 μm, $D_{v0.9}$ data ranges from ∅484 to 814 μm and $V_{<100}$ ranges from 1.2 to 6%$_{vol}$. While these ranges are fairly typical some of the flow rate* and pressure combinations that would be expected to be quite different are very similar. For example data from the 015 flow rate* at 390 kPa shows $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$ values of ∅170, 384, 707 μm, and 2.7%$_{vol}$, respectively. Similarly for the 08 flow rate* at 600 kPa we see values of ∅165, 382, 653 μm and 2.8%$_{vol}$ for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$, respectively. Similar data is seen with the 06 flow rate* at 430 kPa (∅169, 384, 642 μm, and 2.2%$_{vol}$ for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$ respectively). With little change observed across different flow rate* and pressures, the RSM type prediction models did not result in high level fits.

EZK nozzle

The R^2 values for the RSM were 0.83, 0.83, 0.82 and 0.73 for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$ curve fits, respectively. These models showed only marginally better fits than the EZ design. Only pressure was a significant factor for $D_{v0.1}$ (p value of 0.0073). Similar results were seen with $D_{v0.5}$, $D_{v0.9}$, and $V_{<100}$ with only pressure being significant for both (p values of 0.0066, 0.0061, and 0.0197 respectively). The droplet size data supports these results. Regardless of flow rate* by droplet size by spray comparison shows $D_{v0.1}$ values of ∅253, 213 and 210 μm for the 200 kPa spraying pressure, ∅146, 145, 177, 173 and 172 μm for the 400 kPa and finally ∅161, 148 and 139 μm for the 600 kPa. These trends hold for $D_{v0.5}$, $D_{v0.9}$ and $V_{<100}$ as well.

EZKT nozzle

The R^2 values for the RSM were 0.81, 0.78, 0.78 and 0.52 for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$ curve fits, respectively. These models showed lesser fits than either the EZ or EZK nozzle designs. Like the EZK design, only pressure was a significant factor for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ (p value of 0.0219, 0.0280, and 0.0380, respectively). However, none of the factors were significant predictors of $V_{<100}$. From the droplet size data, we can see similar trends to the EZK nozzle, though not with quite the same level of strength (as indicated by the higher p values). At the 200 kPa, $D_{v0.1}$ values were ∅139, 146 and 153 μm, while at 400 kPa were ∅126, 146, 105, 154 and 156 μm, and at 600 kPa were ∅260, 176 and 271 μm. Similar trends are seen with $D_{v0.5}$ and $D_{v0.9}$. This nozzle is not typical compared with most hydraulic nozzles as an apparent increase in droplet size occurred with an increase in pressure, which is also indicated by the decrease in $V_{<100}$ (0.5 to 1.9%$_{vol}$ at 600 kPa compared to 3.1 to 8.8%$_{vol}$ at 200 and 400 kPa).

AZ nozzle

The AZ nozzle showed significantly better models fits with R^2 values of 0.99 for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and 0.98 for $V_{<100}$. Both flow rate* and pressure were significant factors for all droplet size metrics with their interaction and square effects significant in most cases (at the $\alpha = 0.05$ level).

RS nozzle

The RS nozzle also showed good models fits with R^2 values of 0.99 for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and 0.92 for $V_{<100}$. Again, flow rate* and pressure were significant factors for all droplet size metrics with their interaction and square effects being significant in most cases (at the $\alpha = 0.05$ level). The RS nozzle represents that largest span in flow rate* of those tested in the work and the trends in droplet size are much more obvious in its data with the smallest flow rate* showing much smaller droplet sizes and greater fines that the largest flow rate*. One of the exceptions with respect to the significant factors was the flow rate* by pressure effect (p values ranging from 0.1 to 0.38). This is readily apparent in the droplet size data looking at the 20 orifice (flow rate*) data where both the maximum and

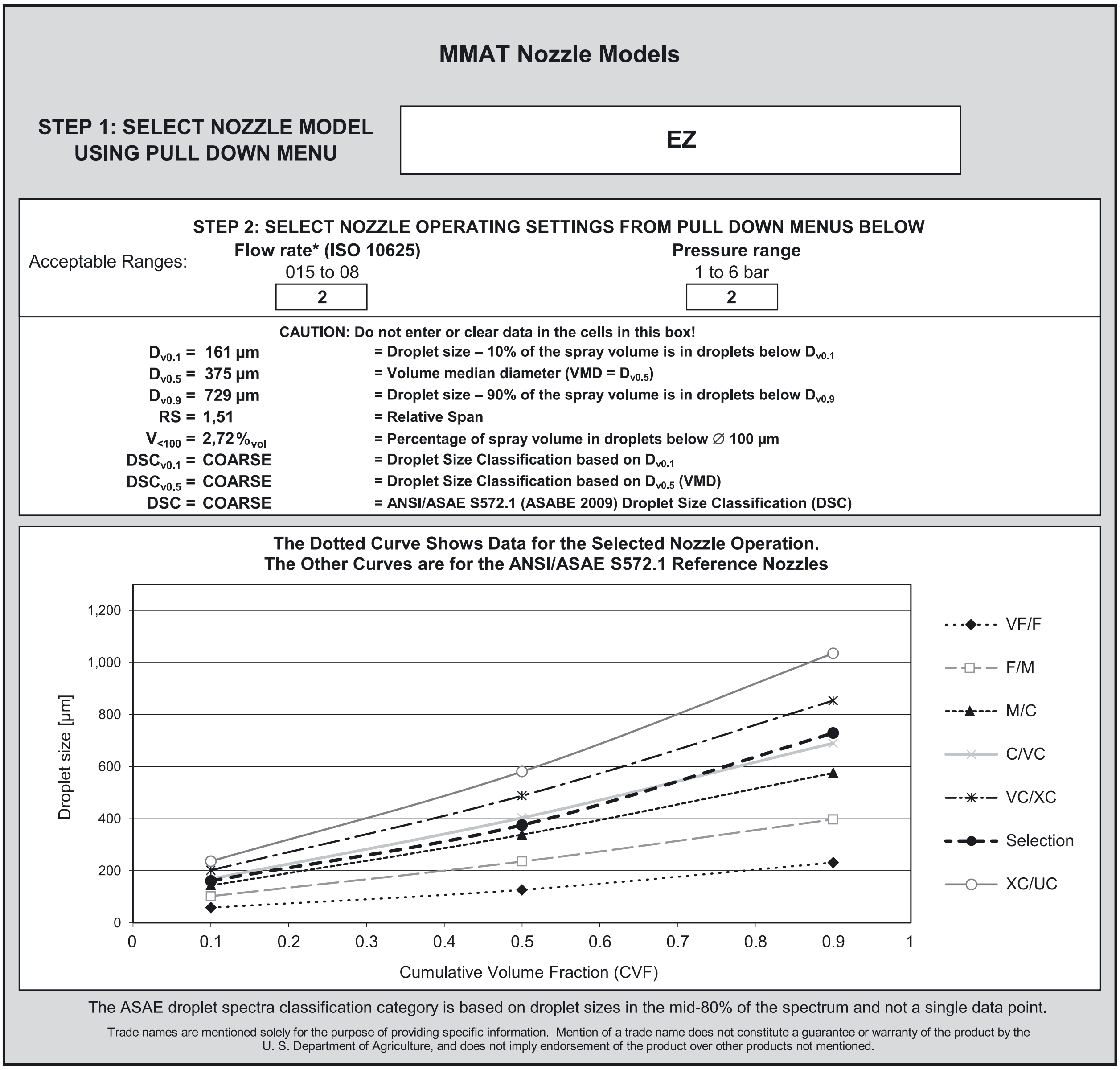

Fig. 1. Excel user interface for MMAT nozzles evaluated as part of this study; VF – Very Fine; F – Fine; M – Medium; C – Coarse; VC – Very Coarse; XC – Extremely Coarse; UC – Ultra Coarse

minimum pressures were evaluated. While droplet size trends were as expected (smaller at higher pressures) the difference is not as dramatic as compared to droplet size for the 03 flow rate* at the same pressure.

Integration into Excel based user interface

The developed models were integrated into an automated user interface (UI) using Microsoft Excel (Fig. 1). The UI requires the user to select the nozzle type followed by selecting the flow rate* and spray pressure combination for which droplet size data is desired. Along with returning the model calculated for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and $V_{<100}$, the data is compared to the ASAE/ANSI S572.1 (ASABE 2009) to determine droplet size classification.

Discussion/Conclusions

Actually don't exist any advising system for atomization characteristics unified with PPP labels. A structured evaluation method was proposed and conducted to evaluated, and ultimately develop a DSS, for agricultural spray nozzles. Measurements of the droplet size spectrum were made for a variety of MMAT nozzles and used to develop the proposed DSS. Using the proposed response surface experimental design method allows for the creation of a computational model which provides droplet size data for a given spray nozzle based on the operational settings. Using the developed model, application treatments can be setup to account for specific scenarios (weather, crop, pest, tank mix, technique) in the field to follow Integrated Pest Management (IPM) requirements (obligation in EC28 since January 2015). The developed models are readily available for use with common spreadsheet software. While the data in this manuscript is limited to a select number of MMAT nozzles, the method proposed can be readily used for any agrochemical hydraulic spray nozzle. This model based method can be professional support for advisors in crop protection and field sprayer operators adequate to different field scenarios. The activation of this model on website, as instrument for increase of crop protection safety and efficiency, will be successful and for free accessed. An enlargement of this model by nozzles from other manufacturers is possible on similar way.

Thanks analyze of tested nozzle set, could be concluded, that the twin jet flat fan air induction nozzle (EZKT) that is not typical with most hydraulic nozzles is an apparent increase in droplet size with an increase in pressure which is also indicated by the decrease sprayed liquid volume in size below ∅100 μm ($V_{<100}$).

The offered option of DSS confirmed big potential of spray characteristics to improve safety and efficiency of PPP application, on very easy and cheap way. Further research according proposed solution, and implementation is possible.

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Appendix

Table A1. Subtraction and division terms (Eq. 1) used to convert factor inputs to model coded inputs (–1 to 1)

Nozzle design	X_1 – Flow rate*		X_2 – Pressure	
	C_{sub1}	C_{div1}	C_{sub2}	C_{div2}
EZ	4.75	3.25	4.25	1.75
EZK	4.75	3.25	4.00	2.00
EZKT	5.00	3.00	4.00	2.00
AZ	3.50	2.50	3.25	1.75
RS	10.90	9.50	3.25	1.75

Table A2. EZ model coefficients

Coefficient	Coefficient terms					
	intercept (A)	flow rate* (B)	flow rate* by flow rate* (C)	pressure (D)	flow rate* by pressure (E)	pressure by pressure (F)
$D_{v0.1}$	177.0940	22.54702	0.717130	–17.4592	–4.58369	–9.33963
$D_{v0.5}$	397.1480	51.43177	4.188014	–40.9629	–1.31967	–19.62580
$D_{v0.9}$	667.2766	46.26003	35.892080	–73.9671	18.98021	–24.52640
$V_{<100}$	2.17296	–1.11595	0.407345	0.965689	–0.446	0.629628

Table A3. EZK model coefficients

Coefficient	Coefficient terms					
	intercept (A)	flow rate* (B)	flow rate* by flow rate* (C)	pressure (D)	flow rate* by pressure (E)	pressure by pressure (F)
$D_{v0.1}$	162.1409	–4.8667	1.176058	–37.6311	4.615500	24.1271
$D_{v0.5}$	358.5630	–4.0688	–1.072300	–76.0660	6.359170	46.2174
$D_{v0.9}$	616.2310	14.8019	–3.162700	–98.1670	4.042849	44.57401
$V_{<100}$	2.731582	0.070268	0.3173	1.16209	0.22939	–0.79334

Table A4. EZKT model coefficients

Coefficient	Coefficient terms					
	intercept (A)	flow rate* (B)	flow rate* by flow rate* (C)	pressure (D)	flow rate* by pressure (E)	pressure by pressure (F)
$D_{v0.1}$	130.7588	–4.86670	28.89528	35.78791	4.61550	24.12710
$D_{v0.5}$	302.6600	11.24138	47.29411	–76.06600	6.35917	46.21740
$D_{v0.9}$	529.8681	34.00733	68.49176	–98.16700	12.13131	76.86829
$V_{<100}$	4.917808	0.13325	0.3173	1.21639	0.22939	–2.06758

Table A5. AZ model coefficients

Coefficient	Coefficient terms					
	intercept (A)	flow rate* (B)	flow rate* by flow rate* (C)	pressure (D)	flow rate* by pressure (E)	pressure by pressure (F)
$D_{v0.1}$	87.0528	25.4032	–5.1014	–16.6774	–5.6825	14.8311
$D_{v0.5}$	205.6732	63.7931	–14.0528	–41.7462	–12.0242	33.3254
$D_{v0.9}$	372.7312	111.8857	–9.4892	–69.8307	–14.7567	47.6947
$V_{<100}$	14.7441	–9.1147	4.3455	5.0899	–1.9917	–4.1195

Table A6. RS model coefficients

Coefficient	Coefficient terms					
	intercept (A)	flow rate* (B)	flow rate* by flow rate* (C)	pressure (D)	flow rate* by pressure (E)	pressure by pressure (F)
$D_{v0.1}$	112.4252	45.1769	–11.2912	–20.7194	–3.7683	16.0732
$D_{v0.5}$	281.1691	127.5347	–32.0592	–38.7040	–4.3229	26.9281
$D_{v0.9}$	569.6825	274.3293	–73.3612	–68.6275	–14.6819	35.4328
$V_{<100}$	6.7168	–11.4429	14.4494	4.8463	–4.8265	–4.7989